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THE AGE OF THE POORAKA FORMATION AND ITS IMPLICATIONS, WITH SOME PRELIMINARY RESULTS FROM LUMINESCENCE DATING

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Summary

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Stratigraphic relationships, supported by luminescence dating, suggest that the Pooraka Formation spans a far greater time interval than previously recognised on the basis of radiocarbon dating and stratigraphic analysis of discrete sedimentary sections. It extends back as far as the Last Interglacial. Re-evaluation of the radiocarbon ages that indicate an interstadial age (i.e. Oxygen Isotope Stage 3: 45 to 30 ka BP) for the sediments is required. Alternatively, a considerable time interval for deposition of the Pooraka Formation would necessitate that the unit be diachronous across the landscape. An age extending back to the Last Interglacial (Oxygen Isotope Substage 5e: c. 125 ka BP) would provide the appropriate palaeo-climates and palaeo-environments for fluvial sedimentation. The revised age has implications for landscape evolution, archaeological and palaeomagnetic prospecting as well as the antiquity of the *Diprotodon* in the Adelaide area.

KEY WORDS: Pooraka Formation, Pleistocene stratigraphy, Last Interglacial, luminescence dating.

Introduction

Large areas of the Adelaide Plains are underlain by the Pooraka Formation (Firman 1967, 1969; Callen *et al.* 1995; Sheard & Bowman 1996), a reddish-brown coloured Pleistocene alluvial deposit with weakly developed calcareous pedogenic horizons that underlies river terraces and alluvial fans. This unit is also widespread beyond the Adelaide Plains, extending on to the Fleurieu Peninsula and into the mid-north of the state, where it flanks the Flinders and Gawler Ranges.

The red-coloured sediments that comprise the widespread Pooraka Formation have been ascribed different names by workers over time and in different areas. For example, they were originally referred to as the 'mammaliferous drift' by Tate (1879) because skeletal remains of the extinct, giant marsupial, *Diprotodon optatum*, were recovered from them in areas to the west of the city of Adelaide. Ward (1966) referred to the sediments as the Christies Beach Formation in the Noarlunga and Willunga sub-basins, Twidale (1968) named them the Klemzig Sand during his investigation of the terraces of the River Torrens, and Bourman (1968, 1969[1]) referred to them as the Adare Clay where they flank the Rivers Hindmarsh and Inman in the Victor Harbor area (Localities shown on Fig. 1). The red-coloured alluvium bears consistent stratigraphic relationships to a younger, grey-black alluvium [Waldeila Formation of Ward (1966), Walkerville Sand of Twidale (1968) and the Breckan Sand of Bourman (1968)], which forms lower terraces and floodplains set within valleys carved out of the red alluvium of the Pooraka Formation. Estuarine shells collected from within the Waldeila Formation in the lower reaches of the Onkaparinga River (Bourman 1972) returned a radiocarbon age of 4,580 ± 160 years B.P. (Bourman 1979). During this middle Holocene time the lower, near-coastal reaches of many streams were shallow, sheltered estuaries as revealed by the presence of fossiliferous marine deposits at depth up valley. This interpretation is supported by evidence from a locality several kilometres from the coast on the lower Onkaparinga River where an aboriginal kitchen midden containing estuarine shells dated at 5,820 ± 90 years B.P. (N.B. Tindale pers. comm. in Twidale *et al.* 1967) is sited on a well drained sand dune site at 20 m asl and adjacent to the former, more extensive estuary.

Ages ascribed to the Pooraka Formation and its equivalents

The Pooraka Formation has generally been ascribed to the Late Pleistocene, with most numerical ages, based on radiocarbon dating, falling within the range of 50,000-20,000 years (see review

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BOURMAN, R.P. (1969) Landform Studies near Victor Harbour. BA (Hons) thesis, The University of Adelaide (unpub.).

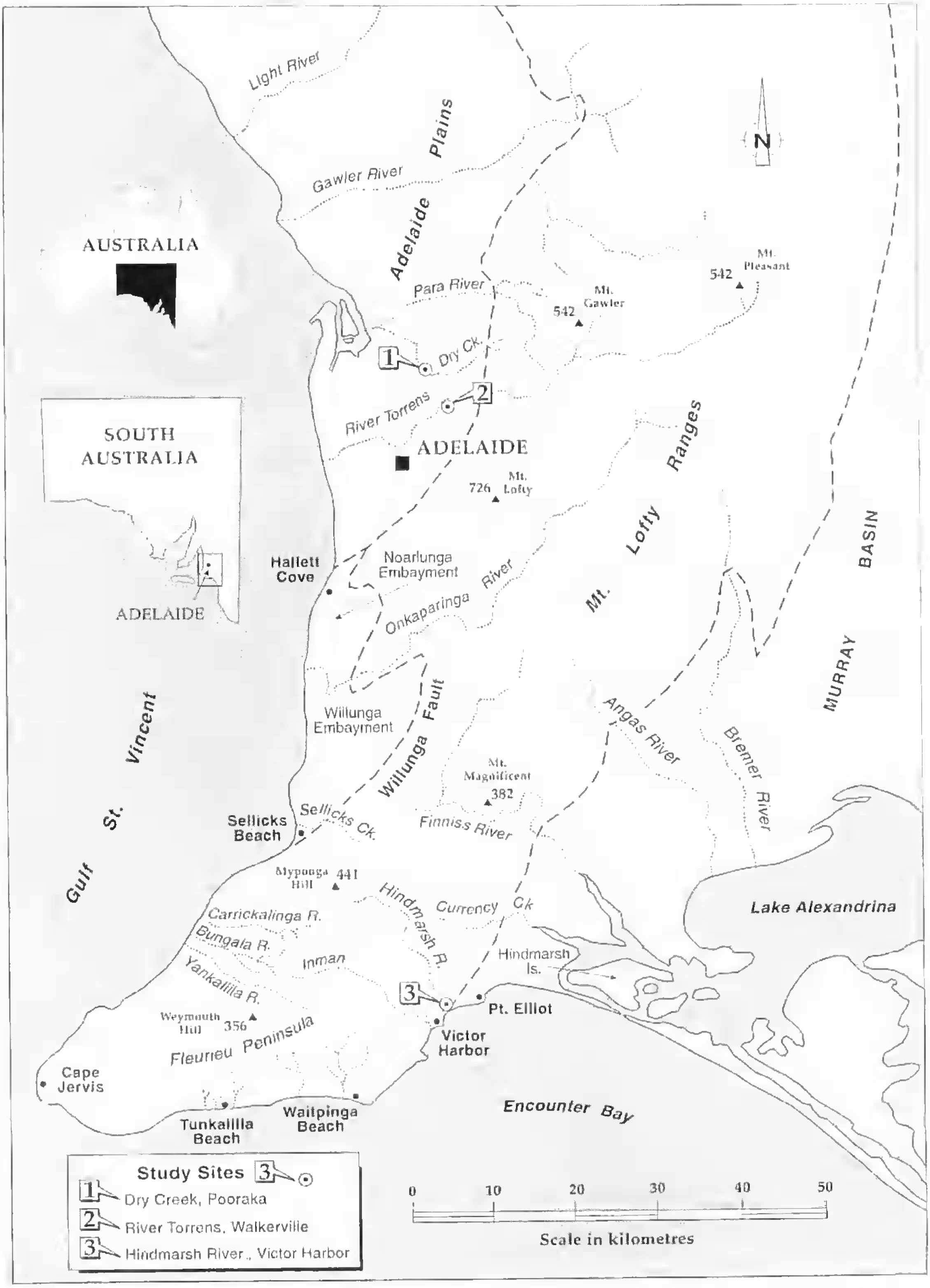

Fig. 1. Location map of sites.

in Callen *et al.* 1995). There has not been universal agreement on to which part of the Late Pleistocene the sediments should be allocated. Twidale (1968) assigned the Klemzig Sand to the Late Pleistocene and demonstrated that it must be older than 6,350 years BP. The distal end of the femur of a giant extinct marsupial, recovered from 3.6 m below the surface of a fillstrath terrace cut into the Adare Clay, in the Hindmarsh River, was dated at approximately 12,600 years BP (Gak - 2356) (Gill & Bourman 1972). Firman (1969) and Daily *et al.* (1976) also considered the Pooraka Formation to be of Late Pleistocene age, but younger than the *Anadara*-bearing Glanville Formation, which is now widely accepted to be of last interglacial age (c. 125,000 yr BP; Murray-Wallace *et al.* 1988; Murray-Wallace & Belperio 1991; Murray-Wallace 1995; Belperio *et al.* 1995). Confident separation between Late Pleistocene Pooraka Formation and earlier Pleistocene alluvial sediments is easily achieved in the coastal zone where they are separated by coastal facies. Inland, on the Adelaide Plains, the Pooraka Formation is readily distinguished from underlying Tertiary sands, the Keswick Clay and the Hindmarsh Clay. The Pooraka Formation is only weakly consolidated, carbonate impregnated and mottled in comparison with the underlying units (Sheard & Bowman 1996). Ward (1966) assigned the Christies Beach Formation to the Last Interglacial as he considered that the surface on it was graded to the last interglacial shoreline (his Epimonasterian high sea level) at approximately + 3 m above present sea level. However, at that time the Last Interglacial was thought to be considerably younger than the present 125,000 years BP.

From the Dry Creek alluvial fan, Williams (1969) described reddish-brown clay overlying older grey-green and red mottled clay, now known to be the Keswick Clay (Sheard & Bowman 1987a,b; M. Sheard pers. comm. 1997). Williams (1969) also noted a calcareous red-brown earth developed within the sediments containing nodules and cylindroids of pedogenic calcium carbonate. A radiocarbon age of 34,600 ± 2700 years BP on carbonised wood from sand 3 m below the land surface was obtained by Williams (1969). The carbonised wood was regarded as detrital in origin and thus was regarded as a reliable representation of the time of deposition. However, if the carbon were detrital, its age should predate the time of sedimentation, which would make the ^{14}C date somewhat older than the time of deposition. The date was taken to indicate a last glacial (Würm) age for the sediments. Further radiocarbon dates supporting a last glacial (Würm) age were derived from a study of alluvial fans on the western side of the Flinders Ranges (Williams 1973). Carbonised detrital wood recovered from depths of 8-9 m and 15 m within the Pooraka Formation provided radiocarbon ages of 33,270 (+ 2130 - 1680 years) BP and > 37,000 years BP respectively.

Stratigraphic observations

Critical evidence concerning the age of the Pooraka Formation occurs at Victor Harbor. Here the relationships between the last interglacial shoreline and the Pooraka equivalent unit, the Adare Clay, suggest that the unit is much older than 50,000 years. Bourman (1968, 1969[1]) established that red-coloured alluvium forms fill-top terraces along the Inman and Hindmarsh Rivers and grades to a shoreline at c. + 6 m above present sea level. The age of the shoreline is considered to be crucial with respect to the age of the terraces and the sediments which underlie them. Twelve species of shells have been identified from this shoreline deposit (Guppy 1943[2]) and it is significant that they contain the sub-fossil *Anadara trapezia*. Initially, Bourman (1968, 1969[1]) followed Sprigg (1952) and assigned these shells to the Holocene. Subsequently, the shells were radiocarbon dated returning ages of 33,170 + 3,180 -2,270 years BP (GaK-5561) and >30,320 years BP (GaK-6099).

Although the above dates are compatible with those of Williams (1969, 1973) they are questionable because the period around 30,000 years BP was a time of low sea level. Furthermore, it is now generally accepted that materials whose true ages are beyond the range of radiocarbon dating (> 40 ka for most laboratories) may yield younger apparent ages, due to the diagenic incorporation of low levels of radiocarbon from modern activity. Thus, materials with an infinite age by radiocarbon dating techniques may yield an apparent age of 37 ka due to the incorporation of 1% ^{14}C with a modern activity (Gupta & Polach 1985). Gill (1974) checked radiocarbon dates of this age against other dating techniques and concluded that radiocarbon dating may be reliable for young materials but older materials may return ages that are far too young. Similar conclusions were reported by Bowman & Harvey (1983) and Belperio *et al.* (1984).

Not only do *Anadara* shells occur at the + 6 m shoreline at the coast at Victor Harbor, but extremely large *Anadara* shells were recovered from a sewer trench c. 1.6 km upstream at a depth of 4 m below the surface, within the Pooraka Formation equivalent unit and at the same absolute elevation of 6 m as at the shoreline (Fig. 2). A drilling programme (CSIRO Soils Division) further revealed the intimate association of *Anadara* shells with the Pooraka Formation equivalent unit, demonstrating that here the *Anadara*, last interglacial deposits (Glanville

[2] GUPPY, D.J. (1943) Geological reconnaissance of part of the Hundreds of Encounter Bay and Goolwa. BSc (Hons) thesis, The University of Adelaide (unpub.).

Formation) and the Pooraka Formation are intercalated coastal and terrestrial equivalents. The *Anadara* shells have been dated both by Uranium-Thorium techniques (100,000-150,000 years BP) and by amino-acid racemisation studies (Kimber & Milnes 1984), which provided results consistent with a last interglacial age.

Methods

The stratigraphic relationships between last interglacial molluscs and the Pooraka Formation

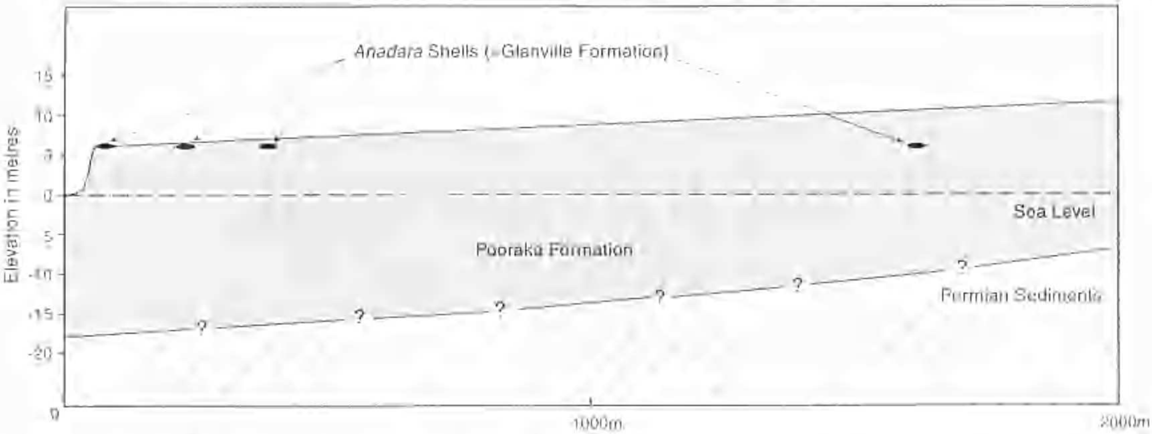

Fig. 2. Sketch section showing the interfingering relationships of the Glanville Formation and the Pooraka Formation in the lower Hindmarsh River at Victor Harbor.

Fig. 3. Photograph of 6 m high river bluff cut in Pooraka Formation sediments downstream of the Bridgeway Hotel on Dry Creek, Pooraka. Maximum section exposed c. 7 m. Red brown earth with associated calcium carbonate zones in upper part of section. At the base of the section the Pooraka Formation rests unconformably on an older Plesitocene unit that closely resembles the Taringa Formation of Ward (1966) but which Sheard & Bowman (1987a,b) consider is more likely to be the Keswick Clay.

equivalent, near the coast, at Victor Harbor provided strong indications that the Pooraka Formation might extend back to the time of the Last Interglacial. In order to test this hypothesis, and to determine whether the inland, terrestrial Pooraka Formation sediments were of an equivalent age, an attempt was made to obtain a numerical age for this formation using the technique of luminescence dating. A key site chosen for sample collection for luminescence dating was the Dry Creek (Pooraka) locality where Williams (1969) collected samples of detrital carbonised wood and carbonate for radiocarbon dating (Fig. 3). Unfortunately, the steep river bluff at this site has now been contoured and landscaped so that it was not possible to sample from exactly the same site as Williams (1969).

A second site on the River Torrens at Walkerville, where a thick Pooraka section had previously been exposed, was selected as a subsidiary luminescence dating sampling site. As both sites have suffered from human modification and landscaping of the former eroding river bluffs it was decided to collect samples for luminescence dating by drilling using an auger drill with an internal push cylinder. This method allowed sampling depths to be determined and the sample to be collected without exposure to light. Two holes were drilled at Pooraka and one at Walkerville. Samples were recovered at depths of 3.5 m, 4.5 m, 4.8 m and 7.5 m (for Pooraka) and 4.5 m, 5.5 m, 6.0 m, 7.5 m, 9.0 m and 9.3 m (for Walkerville). The drilling site at Pooraka was located 7.74 m above the base of Dry Creek and the second site was 11.68 m above the River Torrens level at Walkerville. The same holes were used for both sample collection and scintillometry for dose rate determination. A summary of data collected for the Pooraka and Walkerville samples is shown in Table 1. Sample PK1S from a depth of 3.5 m is close to the level from which Williams (1969) collected detrital carbon for ^{14}C dating.

Luminescence dating methods

Three methods for luminescence dating (LD) of the sediments were used: selective bleach thermoluminescence (TL) of coarse-grain quartz (Prescott & Mojarrabi 1993) and green light stimulated-luminescence (GLSL) of both coarse grain quartz and of fine grain separates (Aitken 1994; Duller 1996). In the dating of sediments it is assumed that exposure to sunlight is the agency that resets the luminescence clock and that the sample has been exposed to sunlight for a sufficiently long time that the stored energy giving rise to the luminescence has been reduced to a low, near zero, level. This is a reasonable assumption in open sites exposed to strong sunlight, but this may not be true where there is the possibility that the material was deposited by, or under, water, as in the present sites, or in a generally colluvial environment. Both the TL selective bleach and GLSL methods seek to overcome this uncertainty by making use of an easily-bleached component which can be reset to zero by short exposure to sunlight. It is assumed that this component has, in fact, been reset. Details of the methodology are presented in the appendix.

Dating results

Pilot TL runs were carried out on coarse grain quartz from all samples except PK2S/4.8, WV1S/7.5 and WV1S/9.3. Such runs are designed to assess whether the sample is likely to be datable and, if so,

TABLE 1. *Summary of collected data for Pooraka and Walkerville samples.*

SAMPLE	PPM U	PPM Th	PPM U DNA	PPM Th DNA	PPM U Sct.	PPM Th Sct.	%K XRS	%K Sct	%H_2O
PK1S/3.5	1.5 ± 0.6	7.0 ± 2	1.48 ± 0.11	7.23 ± 0.5	1.74 ± 0.17	7.12 ± 0.29	1.08 ± 0.03	0.86 ± 0.02	6.8 ± 0.07
PK2S/4.5	1.1 ± 0.3	7.8 ± 1	1.26 ± 0.11	7.31 ± 0.4	1.75 ± 0.17	7.68 ± 0.29	0.89 ± 0.03	0.82 ± 0.02	3.7 ± 0.06
PK2S/4.8	1.1 ± 0.5	6.3 ± 1	1.10 ± 0.10	6.24 ± 0.4	1.34 ± 0.16	6.76 ± 0.28	0.89 ± 0.03	0.91 ± 0.03	4.4 ± 0.07
PK1S/7.5	1.2 ± 0.6	7.1 ± 2	1.22 ± 0.10	6.91 ± 0.4	1.74 ± 0.17	9.69 ± 0.32	1.20 ± 0.04	1.13 ± 0.03	12 ± 0.07
WV1S/4.5	1.8 ± 0.3	12 ± 1	1.81 ± 0.12	11.7 ± 0.5	1.89 ± 0.24	12.5 ± 0.44	1.85 ± 0.06	1.60 ± 0.04	8.8 ± 0.07
WV1S/5.5	1.6 ± 0.6	14 ± 2	1.93 ± 0.13	12.6 ± 0.6	2.33 ± 0.24	10.5 ± 0.42	1.81 ± 0.05	1.32 ± 0.04	7.5 ± 0.07
WV1S/6.0	1.9 ± 0.5	10 ± 1	1.86 ± 0.12	10.3 ± 0.6	2.47 ± 0.25	12.1 ± 0.48	1.59 ± 0.05	1.54 ± 0.04	8.3 ± 0.07
WV1S/7.5	1.7 ± 0.5	11 ± 2	1.66 ± 0.12	11.8 ± 0.6	2.66 ± 0.26	11.1 ± 0.47	1.71 ± 0.05	1.49 ± 0.04	15.7 ± 0.07
WV1S/9.0	1.8 ± 0.5	13 ± 1	1.77 ± 0.12	13.4 ± 0.6	2.95 ± 0.29	13.4 ± 0.50	2.19 ± 0.07	1.71 ± 0.04	18.0 ± 0.07
WV1S/9.3	1.2 ± 0.5	15 ± 2	1.88 ± 0.13	13.0 ± 0.6	2.95 ± 0.29	13.4 ± 0.50	1.98 ± 0.06	1.71 ± 0.04	16.4 ± 0.07

The first two columns are the results derived from Thick Source Alpha Counting. A DNA was done for uranium only: ppm Th (DNA) were obtained by combining the count-rate from thick source alpha counting and the uranium concentration from DNA. ppm U Sct, ppm Th Sct & %K Sct were derived from the on-site gamma ray scintillometry data.

to give a limited-accuracy estimate of the acquired luminescence and the sensitivity to radiation, and hence plan the schedule for a complete dating procedure. A pilot run consists of eight discs; half of these are bleached, after which two discs each of bleached and unbleached are given a radiation dose of 60 Gy. For all samples except PK1S/3.5, the shallowest of the Pooraka samples, the TL was clearly saturated and no further work on them was justified. Although PK1S/3.5 was approaching saturation, a full dating procedure was carried out for both TL and GLSL.

Such procedures give the Equivalent Dose, D_e, a measure in grays of the energy absorbed by the sample from radiation in the environment since it was last reset to zero. The age of the sample is found by dividing the equivalent dose by the dose rate in gray per kiloyear (Gy ka^{-1}).

Equivalent doses, dose rates and ages

TL glow curves are shown in Figure 4a, shine-down curves in Figure 4b and corresponding dose curves are shown in Figures 5a, b respectively. None of the curves is scaled. It is evident that the dose curve of quartz (Fig. 5a) is close to saturation but that the growth curve for GLSL on fine grains (Fig. 5b) has a different shape and the curve continues to rise quasi-linearly for high doses. This is because the

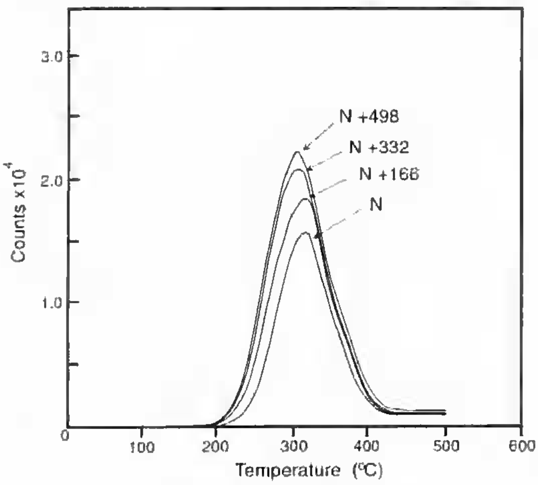

Fig. 4a. Glow curves for sample PK1S/3.5. The figures next to each curve indicate the dose in Gy.

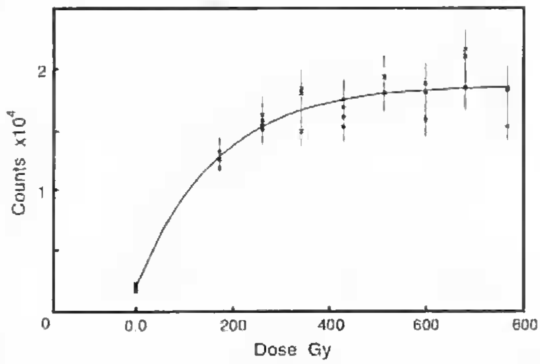

Fig. 5a. TL growth curve for sample PK1S/3.5 for the 10° interval at 305° C. For Figures 5a and b, the curves are fitted by the "Australian slide" method: the (natural + dose) points are shown by crosses; the (bleached + dose) points are shown by circles. There is an apparent sensitivity change for the TL bleached curve but the scaling factor does not differ significantly from unity.

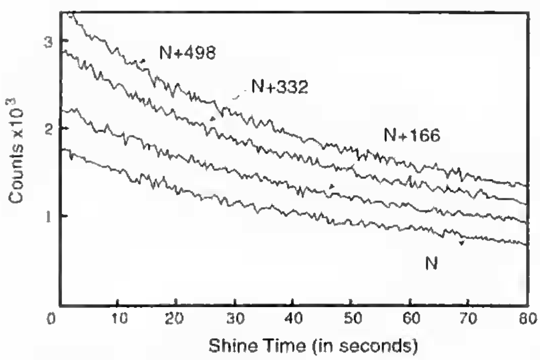

Fig. 4b. GLSL shine-down curves for sample PK1S/3.5. The figures next to each curve indicate the dose in Gy.

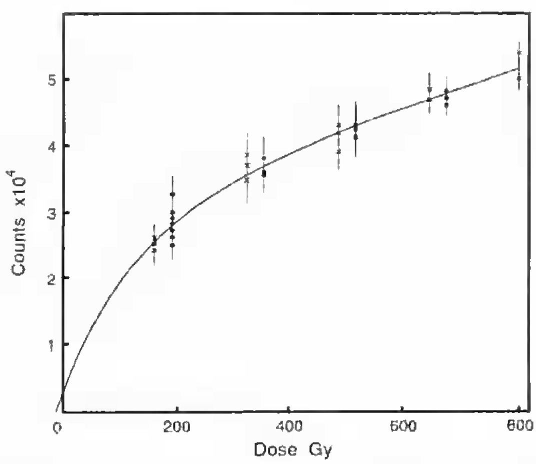

Fig. 5b. GLSL growth curve for sample PK1S/3.5 integrated over the first 100 s.

TABLE 2. *Equivalent doses, dose rates and ages for sample PK 1S/3.5.*

	COARSE GRAINED QUARTZ		FINE GRAINS	
	selective bleach TL	GLSL	GLSL	IRSL
D_e Gy	249 ± 58	208 ± 44	294 ± 15	> 250
dose rate	TSAC/DNA/XRS	SCINT	TSAC/DNA/XRS	SCINT
Gy ka^{-1}	1.99 ± 0.06	1.96 ± 0.04	2.54 ± 0.12	2.54 ± 0.11
Weighted mean	1.97 ± 0.03		2.54 ± 0.08	
age ka	126 ± 29	105 ± 22	116 ± 6	> 100

undifferentiated fine grains consist of a mixture of minerals in which quartz and feldspar are dominant. Thus although the quartz component saturates, the feldspar component does not. Equivalent dose values from all three methods appear in the first line of Table 2. It will be noted that the two methods of finding D_e give different values; this is characteristic of the methods.

Two distinct methods for finding the dose rates were used (described in the appendix), the aim being to get two independent values for each sample, to improve the statistical precision and as a check on the presence of radioactive disequilibrium (Prescott & Hutton 1995). The values obtained are included in Table 2. As with D_e, dose rates differ for coarse and fine grains. The values are in excellent mutual agreement and this shows that radioactive disequilibrium is absent.

The weighted mean dose rates are shown on line 3; line 4 shows the ages derived from the D_e using the age equation from the appendix. The weighted mean, 116 ± 6 ka is dominated by the GLSL determination for fine grains.

Comment

Allowing for statistical fitting uncertainties, all three ages are in good agreement. Bearing in mind that they are based on different physical processes, all of which assume that the luminescence signal was set to zero in the past, it shows that this was very likely the case and that the age being determined is indeed the time of deposition. If it is not so, the apparent ages will be too large.

As already mentioned, the dose growth curve of Figure 5a, which is for quartz TL, shows that the luminescence is close to saturation. For this reason the estimate of relative uncertainty given by the analysis is large. This is also true for GLSL of quartz. For GLSL of fine grains, on the other hand, the presence of the feldspar component allows D_e to be found with significantly better precision.

The best estimate of the time of deposition of sample PK1S/3.5 is the weighted mean age, 116 ± 6 ka. In fact, this is dominated by the GLSL determination on fine grains. It is probably best to regard the quartz determinations by selective bleach and GLSL as being supportive of the GLSL fine grain age. At the two standard deviation level the age exceeds 104 ka. Consistent with these numbers, the saturation of the luminescence of all the other samples shows that they are as old or older than this. Therefore, although only one sample has yielded a numerical age, there is enough evidence to establish a lower limit to the age of the formation and it is in support of the geomorphological and sedimentological evidence.

In addition to the three methods already described, infra-red stimulated luminescence (IRSL) of fine grains (Wintle 1994) was tried. IRSL uses only feldspars and is less susceptible to saturation, although it may be subject to long-term fading. Although the growth curve was similar in shape to the GLSL curve of Figure 5a, the statistical fitting procedures did not satisfy our criteria for an acceptable D_e, beyond showing that it was greater than 100 ka. Whether this is due to the sample or the methodology remains to be determined. However, the result is sufficiently encouraging to suggest that it may be possible to find ages from the lower levels at Pooraka and for Walkerville where quartz methods were unsuccessful.

Discussion

The location of the date derived from the upper section of the Pooraka Formation at a depth of 3.5 m below the surface is in complete accordance with the numerical age obtained of 116 ± 6 ka, with the Last Interglacial ranging from approximately 132-118 ka (see Chen *et al.* 1991; Lambeck & Nakada 1992; Zhu *et al.* 1993; Stirling *et al.* 1995; Eisenhauer *et al.* 1996). The GLSL technique offers the possibility of obtaining a luminescence date for lower sections of the Pooraka Formation thereby facilitating the calculation of the rates of sedimentation during the Last Interglacial; it may be that sedimentation during warmer, wetter, last interglacial times was quite rapid and this technique offers the opportunity to test this idea.

These results suggest a far greater age range for the Pooraka Formation than has previously been recognised. In the past, the age of the Pooraka formation has been poorly constrained at about 20-30 ka BP, possibly because of the now-known limitations of radiocarbon dating. Furthermore, it should be noted that other methods such as TL, GLSL and IRSL were not available when many of the radiocarbon dates were carried out.

Many observations and cores indicate that, in places, the Pooraka Formation appears to be younger than the last interglacial Glanville Formation, especially in subsiding areas. For example, Ludbrook (1976) in the Port Adelaide area described Pooraka Formation overlying calcreted Glanville Formation, which in turn overlay Hindmarsh Clay. Belperio and Rice (1989) showed that of 62 cores from the Gillman area, 11 record the sequence of Holocene overlying calcreted Glanville Formation without Pooraka Formation, and 5 record Holocene overlying Pooraka which overlies calcreted Glanville Formation. The calcreted surfaces are interpreted as pedogenic features developed during subaerial exposure and would have formed prior to the deposition of the overlying sediments of the Pooraka Formation. In contrast, four of the cores record a sequence of Holocene/Pooraka/Glanville Formation, without a well-developed calcrete on the Glanville Formation, and one records intermixing of Pooraka and Glanville. These last cores may indicate coeval Glanville and Pooraka sedimentation or little time break between the two.

Extensive work by Sheard & Bowman (1996), which involved drilling cores to depths of 10 m at 170 sites over the Adelaide Plains, intersected Pooraka Formation in 80 cores. This work corroborates the findings of Belperio & Rice (1989) for the coastal zone. More landward sites indicated the sequences to be: Holocene/Pooraka/Keswick Clay/Hindmarsh Clay and Holocene/Pooraka/Keswick Clay/Tertiary sands or Adelaidean rocks. At the 80 sites intersecting Pooraka Formation sediments, Sheard & Bowman (1996) rarely experienced difficulties in identifying Pooraka Formation from the overlying and underlying materials (M. Sheard pers. comm., 1997).

Recent drilling work by Woodhead *et al.* (1995[1]) for Baulderstone Hornibrook in the Holdfast Shores (Glenelg Patawalonga Redevelopment area) has demonstrated that deposits of Pooraka Formation 2-4 m thick occur well offshore from the present coast line. These deposits are detached from more landward deposits either by zones of non-deposition or by early Holocene erosion. Variable stratigraphic relationships are apparent in this locality. For example, the following relationships of Holocene/Pooraka/Glanville/Hindmarsh Clay, Holocene/Glanville/ Hindmarsh Clay or Holocene/ Fulham Sand/Pooraka/Glanville/Hindmarsh Clay/ occur within an 800 m east-west section.

It may be that the Pooraka Formation was deposited over a considerable period of time. This view is also supported by the occurrence of palaeosols within Pooraka Formation equivalent sediments as exposed in Sellicks Creek and Cobblers Creek. The luminescence data indicate an age approximately coincident with the Last Interglacial (125 ka BP), but the results at any one place may be influenced by the terrestrial/marine interactions. For example, if there is not an active supply of alluvium to the coastline then marine deposition, exposure and calcrete formation will dominate, in places subsequently mantled by Pooraka or Holocene sediments. It may be that only where there is a sufficient supply of terrestrial sediments to the coastline, such as where streams debouch at the coastline in relatively constrained valleys (e.g. Hindmarsh River at Victor Harbor), that the interfingering characteristics of the two sediments can be demonstrated. It is also possible that Pooraka Formation sediments do not reach the position of the Glanville Formation until after it has been calcreted. It should be noted that much of the Pooraka Formation has been deposited inland, well beyond the elevation and planimetric position of the last interglacial shoreline, so that in these situations there is no clear stratigraphic relationship between the two units.

Implications of the Pooraka Formation extending back to the Last Interglacial

If the interpretation that the Pooraka Formation extends back to the Last Interglacial is correct, a re-evaluation of the radiocarbon ages that indicate glacial or interstadial ages for the sediments is required. Alternatively, the conflicting results may suggest that there could be sediments, which

[1] WOODHEAD, FIRTH, LEE & ROSE PTK Pty Ltd (1995) Appendix 3 Geotechnical Investigations for Holdfast Shores in Baulderstone Hornibrook Glenelg Coastal Works and Ferry Wharf Report to Urban Projects Authority of SA (unpub.).

although appearing similar, occupy a range of ages.

At a number of locations, the Pooraka Formation has been noted to overlie the Glanville Formation with a variably developed calcrete, suggesting surface exposure prior to burial by younger Pooraka Formation sediments. Elsewhere, such as in the lower Hindmarsh River, where there is an interplay of coeval coastal and terrestrial events, the stratigraphic relationships between the Pooraka and Glanville Formations may simply represent a facies change and not a geological succession. A considerable time interval may be required for the deposition of the Pooraka Formation so that its age could be diachronic, with deposition occurring during the rise in sea level up to and beyond that of the last interglacial level.

A last interglacial age provides appropriate palaeoclimatic and palaeo-sea level conditions for explaining the distribution of the Pooraka Formation. Close to the coast the unit relates to a shoreline higher than the modern one, while inland the wetter, interglacial conditions would have favoured aggradation of sediments as opposed to drier, glacial conditions that would have facilitated dissection. This timing would also ensure sufficient time both for the build up of extensive deposits of the Pooraka Formation over large areas including much of the city of Adelaide, and time during glacials and interstadials for erosion of the Pooraka Formation to develop the extensive terrace system of the River Torrens (Twidale 1968).

A last interglacial age for the Pooraka Formation is of significance for archaeological prospecting. At the present time there is debate concerning the antiquity of humans on the Australian continent. Substantial changes in vegetation related to Aboriginal burning practices have been interpreted as resulting from human impact and used to infer the arrival of people in Australia as long ago as 140,000 years (Kershaw *et al.* 1993; Kershaw 1993, 1994, 1995). These claims have been questioned by various workers (e.g. Anderson 1994; Hope 1994; White 1994; Webb 1995). If the Pooraka Formation is of last interglacial age it may present a prospecting opportunity to test if Aboriginal colonisation had occurred in southern Australia prior to 125,000 years BP during the time of the penultimate glacial low sea level.

A minor palaeomagnetic event, the so-called "Blake Event", has been identified in the northern hemisphere in loess sequences (Hongbo *et al.* 1995) at approximately 120 ka. Given that the general age of the Pooraka Formation is almost certainly of last interglacial age, and that the upper part of the formation has been ascribed a GLSL age of 116 ± 6 ka, there may be opportunities to identify the Blake event in the southern hemisphere.

A last interglacial age for the Pooraka Formation has implications for the antiquity of the *Diprotodon* in the Adelaide area. Diprotodontid remains have been recorded well back into Tertiary strata in the North Flinders-Callabonna Plains areas (Callen & Tedford 1976; Pledge & Tedford 1990; M. J. Sheard pers. comm. 1997.) but not, so far, in the Adelaide area. Discoveries of *Diprotodon* remains have been made in the Pooraka Formation (Twidale 1968; N. Pledge pers. comm. 1996) of the Adelaide area and while the *Diprotodon* may have predated and survived well beyond the age of this sedimentary unit, it was almost certainly roaming the swampy, aggrading Adelaide Plains some 125,000 years ago.

The age has further implications for landscape evolution as there appears to have been a major erosional hiatus of some 120,000 years between the deposition of the Pooraka Formation and the grey-black Waldeila Formation, which is of mid-Holocene age. There were no sea levels higher than the present in the intervening period so that erosion would have dominated this interval of time. Alternatively, any sediments deposited during this time could have been removed in late stages of erosion.

Conclusions

The main conclusion from this work is that the Pooraka Formation must span a far greater time period than previously recognised, probably extending as far back as Last Interglacial time i.e. 125 ka. It appears that the tectonic and environmental setting, which influences the supply of terrestrial sediments to the coastline, is of extreme importance in interpreting the stratigraphic relationships between the Pooraka Formation and the Glanville Formation. Much more luminescence dating work is required to constrain or document the age ranges in different settings i.e. in the Victor Harbor setting where the two are intermixed, in contrast to the Port Adelaide setting where a major calcrete palaeosol separates them. We may expect luminescence dating techniques to document ages from last interglacial times, possibly through to 30-50 ka, if the quartz grains are sufficiently reset. This offers the possibility of providing a more reliable dating tool than radiocarbon techniques, which still struggle to provide meaningful dates past 40 ka.

The red-brown alluvial sediments, referred to as Pooraka Formation and equivalents, are considered to extend back to at least the Last Interglacial of c. 125,000 years BP. This is demonstrated by the stratigraphical relationships of the red-brown sediments to both younger and older sediments, the interdigitating of demonstrated last interglacial marine deposits with them, then grading to a + 6 m higher shoreline containing last interglacial marine fossils at Victor Harbor, and the fact that a higher sea level, together with associated warmer and wetter conditions would favour aggradation, whereas colder, drier glacial conditions associated with lower sea levels would have favoured erosion. All of these factors support a last interglacial age.

The luminescence data have demonstrated viability as an independent means of testing the hypothesis that the Pooraka Formation is of last interglacial age. Fluvial sediments present special problems for luminescence dating because the sediments being water-deposited, may not have been exposed to sunlight for sufficiently long to zero the quartz grains, resulting in inherited saturation levels within the grains. A further complication may be that in the Adelaide area, the sediments may have not been transported sufficient distances for the quartz grains to have been zeroed. Given these constraints, it is extremely gratifying that it was possible to achieve a reliable luminescence age for the Pooraka Formation at Dry Creek, offering the possibility of further advance in this area.

An aim of this project was to establish the effectiveness of luminescence as a dating technique for Quaternary fluvial sediments in order to resolve differing interpretations of their ages and to facilitate correlation of river terraces in different valley systems. Clearly, there is a need for many further dates to be obtained from river terrace and alluvial fan deposits over wider-ranging areas to verify the conclusions of the present work. However, the implications of an age for the Pooraka Formation extending back to the Last Interglacial are so significant that our preliminary results are presented here and provide the basis for further study.

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Appendix: Methodology for luminescence dating

Quartz grains (90-120 μm) were extracted as described in Huntley *et al.* (1993). Briefly, pure quartz of the right size was obtained by pretreating with HCl, followed by NaOH to break up clay aggregates, sieving, etching with 40% HF for 40 minutes at 20° C, magnetic separation and floating on heavy liquid at specific gravity 2.67. For measurement, 5.0 ± 0.1 mg was deposited on stainless steel discs. Individual discs were post glow dose normalised with 6 Gy.

Fine grains (undifferentiated as to mineralogy) were separated after the HCl and NaOH extractions by settling from aqueous 0.01N NaOH, the 4-11 μm fraction being retained. This was then deposited on aluminium discs from acetone suspension, about 1 mg per disc. Individual discs were 0.5 s short-shine normalised.

As stated in the main text, both dating protocols make use of the easily bleached component of luminescence. In the case of TL this component is selected for by both temperature and wavelength of emission (Prescott & Mojarrabi 1993). For GLSL it is assumed that the stimulated emission comes from the easily-bleached component; optical filters also select for this component (Huntley *et al.* 1991). The output is expressed as intensity as a function of temperature for TL and as a function of shine-down time for GLSL.

For both protocols the emitted intensity is measured for "natural" samples and for samples which have received additional doses from a calibrated laboratory beta-source (N+ß). About half of these samples are exposed to laboratory bleaching by sunlight filtered by a 475 nm long-wavelength-pass filter (Chris James 101); this bleach removes the rapidly bleaching component completely. Some bleached discs are also irradiated (YB+ß) to provide the shape of the "missing" part of the dose curve at doses less than the natural dose. The data analysis follows the so-called "Australian slide" procedure (Readhead 1988; Prescott *et al.* 1993) and the data output is the equivalent dose D_e expressed in grays. Such curves are known as "dose curves".

Two methods of dose rate determination were used: *In situ* scintillometry (see e.g., Hutton & Prescott 1992) uses a sodium iodide scintillation crystal, 75 mm x 75 mm diameter in the auger hole from which the sample for dating is taken. The instrument is calibrated for K, U and Th and, independently, for total gamma ray dose. Scintillometry gives a completely self-contained measure of dose rate.

Thick source alpha particle counting (TSAC) (Jensen & Prescott 1983; Huntley *et al.* 1986) gives a value for the contribution to the dose rate from U and Th together, and an estimate of the U and Th concentrations separately. In fact, the dose rate to the sample is effectively determined by the total alpha count and is almost independent of the relative amounts of U and Th. However, the measured ratio allows a (small) adjustment to be made to the dose rate. Combined with measurement of K, TSAC gives an independent measure of dose rate. X-ray fluorescence spectrometry is used to find K.

In addition, U was found using delayed neutron activation (DNA). If this differs significantly from the other methods of assay for uranium, it gives an indication of radioactive disequilibrium, which was not the case here. It is most conveniently combined with the data from alpha counting to give the U concentration and hence a more accurate value for Th. These are the values shown in Table 1.

Table 1 includes the elemental analyses for all samples. The dose rates calculated for PK1S/3.5 using the conversion factors of Nambi & Aitken (1986) are shown in Table 2. The water content measured at the time of sampling was used in the dose rate calculations. Cosmic ray dose rates have been added in (Prescott & Hutton 1994). All data are included in Table 1, even though a numerical age was found for only one sample.

The age calculation is conveniently expressed in terms of the so-called "Age Equation":

$$\text{Age (ka)} = \frac{\text{TL of sample}}{\text{TL per unit dose (TL/Gy)} \times \text{dose rate (Gy ka}^{-1}\text{)}}$$

In this equation, "TL of sample" (which measures the accumulated energy) and "TL per unit dose" (which defines the sensitivity of the material to radiation) are measured in the laboratory on quartz or fine grains extracted from the sample; and "dose rate" is determined from measurements in the field and/or laboratory.